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The Johns Hopkins University Center for Nondestructive Evaluation (CNDE) has pioneered the development of non-contact remote ultrasonic technology. In this project, we have developed, optimized, and applied non-contact ultrasonic methods of non-intrusive, remote inspection of advanced materials and assessed the feasibility of this technology for implementation on Naval structures. Ultrasonic testing of material properties is a demonstrated technology and has proven to be a robust industrial tool. The major difficulty in ultrasonic testing is the conventional need to use contact transducers with the associated mechanical coupling materials. We have further demonstrated non-contact methodology for the materials characterization that should enable in situ and on platform assessment of structural degradation due to fatigue or corrosion for metals and composites. Implementation of these measurements would result in considerable risk reduction and cost savings to the Navy while permitting rapid inspection of large areas of Naval structures, including those made of metal, ceramics, polymers, composites and hybrid combinations of materials.

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APPLICATION OF NON-CONTACT HYBRID ACOUSTICAL TECHNIQUES FOR REMOTE INSPECTION OF NAVAL STRUCTURES

B. Boro Djordjevic and Robert E. Green, Jr.
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1.0 ABSTRACT

Existing and new Naval structures require improved nondestructive evaluation (NDE) techniques. Existing metallic structures are suffering from corrosion and fatigue damage, while many newer structures utilize advanced composites for which nondestructive evaluation methods have not been optimized. Aging NAVAIR platforms require more extensive NDE for structural verification and detection of corrosion and fatigue damage. The Navy is also committed to implement composites in advanced sails, helicopter components, V22 Osprey, masts, bulkheads, aircraft elevators and other structural components.

The Johns Hopkins University Center for Nondestructive Evaluation (CNDE) has pioneered the development of non-contact remote ultrasonic technology. In this project we have developed, optimized and applied non-contact ultrasonic methods for non-intrusive, remote inspection of advanced materials and assessed the feasibility of this technology for implementation on Naval structures. Ultrasonic testing of material properties is a demonstrated technology and has proven to be a robust industrial tool. The major difficulty in ultrasonic testing is the conventional need to use contact transducers with the associated mechanical coupling materials. In this project, we have further demonstrated non-contact methodology for the materials characterization that should enable in situ and on platform assessment of structural degradation due to fatigue or corrosion for metals and composites. Implementation of these measurements would result in considerable risk reduction and cost savings to the Navy while permitting rapid inspection of large areas of Naval structures, including those made of metal, ceramics, polymers, composites, and hybrid combinations of materials.

2.0 BACKGROUND

2.1 CONTACT ULTRASONICS

Currently, poled ferroelectric ceramics are most often used as ultrasonic transducer materials. A major problem associated with conventional techniques is the requirement that the piezoelectric transducers be acoustically bonded to the test material with an acoustical impedance matching coupling medium such as water, oil, or grease or the ultrasonic test is performed using water immersion of the part. Although the couplant allows acoustical energy to propagate into the test material, it causes several problems in addition to potential harm to the material. For velocity measurements, which are necessary for material thickness measurements, to determine the depth of defects, the coupling medium can cause transit time errors on the order of several percent. Due to

partial transmission and partial reflection of the ultrasonic energy in the coupling layer, there may be a change of shape of the waveform, which can further affect velocity measurement accuracy. This can also lead to serious errors in absolute attenuation measurements of up to twenty percent of the measured values. This latter fact is the reason that so few reliable absolute measurements of attenuation are reported in the scientific literature. It is also important to note that the character of the piezoelectric transducer itself exerts a major influence on the components of the ultrasonic signal, since conventional transducers have their own frequency, amplitude, and directional response. In addition, they "ring" at their resonance frequency and it is extremely difficult to distinguish between the amplitude excursions and frequency alterations caused by this "ringing" and the actual characteristics of the ultrasonic signal.

2.2 NON-CONTACT ULTRASONICS

A method of remote non-contact generation and detection of ultrasound is therefore of great practical importance. Non-contact techniques afford the opportunity to make truly non-contact ultrasonic measurements at elevated temperatures, in geometrically difficult to reach locations, and to do this at relatively large distances from the test structure surface. Several such techniques are presently available in various stages of development, namely capacitive pick-ups, electro-magnetic acoustic transducers (EMATs), laser beam optical generators and detectors, and more recently air(gas)-coupled ultrasonic systems. However, as the name implies, capacitive pick-ups cannot be used as ultrasonic generators and, even when used as detectors, the air gap required between the pick-up and test structure surface is extremely small, which in essence causes the device to be very nearly a contact one.

EMATs, on the other hand, have been successfully used for material defect characterization particularly in metal bars, tubes, pipes, and plates. One major problem with EMATs is that the efficiency of ultrasound generation and detection rapidly decreases with lift-off distance between the EMATs face and the surface of the test object. They can obviously only be used for examination of electrically conducting materials. Because of the physical processes involved, they are much better detectors than generators of ultrasound.

Laser beam ultrasound generation and detection affords the opportunity to make truly non-contact ultrasonic measurements in both electrically conducting and non-conducting materials, in materials at elevated temperatures, in corrosive and other hostile environments, in geometrically difficult to reach locations, and do all of this at relatively large distances, i.e. meters, from the test object surface. Furthermore, lasers are able to produce both shear and longitudinal bulk wave modes as well as Rayleigh and plate modes. However, laser based interferometric detectors suffer from the fact that they can only be used to detect ultrasonic waves on surfaces which are good reflectors of light at the same wavelength as the laser used in the interferometric detector.

Air(gas)-coupled ultrasonic systems have been under development for some time and they are currently being rapidly optimized for practical non-contact ultrasonic

applications. These systems are more similar to conventional contact ones and, therefore, when optimized will play an important role in modern nondestructive evaluation.

Researchers in the Johns Hopkins University Center for Nondestructive Evaluation (CNDE) have pioneered the development and application of non-contact ultrasonics systems, including hybrid ones, which use laser generation/EMAT detection or laser generation/air-coupled detection. **Figure 2.1** illustrates the type of ultrasonic transducers available for the testing. These systems have proven to be optimum for a number of materials characterization applications including nondestructive characterization of lumber, composite prepregs, composite panels, inspection of aircraft aluminum panels, oil tanker tank steel and railroad rails and control of the fiber placement process,

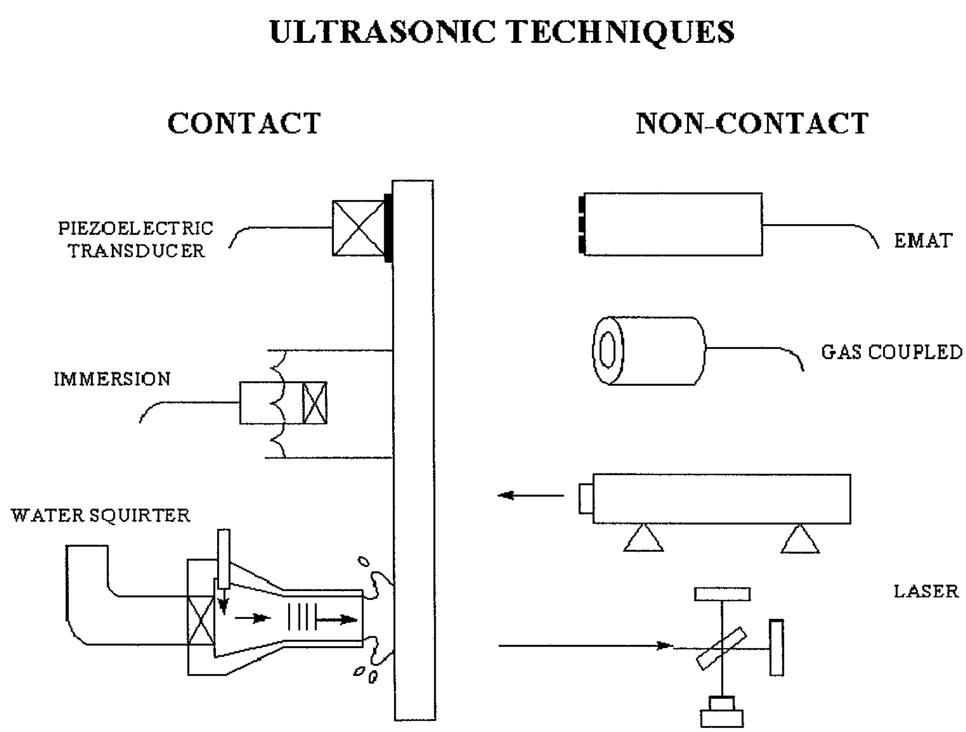


Figure 2.1: Generic contact and non-contact ultrasonic transducers.

2.3 FATIGUE DAMAGE DETECTION

2.3.1 Fatigue Damage Background

Since Naval aircraft of current design are complex, expensive structures and since the present funding situation severely limits the construction of new aircraft, there is an ever increasing demand to assure the longer safe service life of components prior to maintenance disassembly and replacement. Unnecessary time spent on the ground is uneconomical from a financial viewpoint and can be disastrous from a military viewpoint.

Therefore, it is imperative that advanced reliable nondestructive evaluation techniques be developed to detect both fatigue and corrosion damage in aircraft currently in service.

Fatigue damage resulting in microcrack and subsequent macrocrack formation constitutes one of the primary mechanisms for loss of structural integrity leading to failure of aircraft components. It has been well documented for all types of fractures that nucleation of cracks in metals occurs as a result of inhomogeneous plastic deformation in microscopic regions. This inhomogeneous plastic deformation can be in the form of slip bands, deformation bands, mechanical twinning, or localized strain concentrations at grain boundaries, precipitates, dispersed particles, and inclusions. Moreover, the mechanisms responsible for these regions of inhomogeneous plastic deformation are all based on dislocation interactions. In particular, dislocation interactions with point defects, with other dislocations, with stacking faults, with grain boundaries, and with volume defects are known to create regions of severe localized plastic deformation, which develop into microcracks, and these, in turn, either coalesce or grow into macrocracks leading to ultimate fracture.

Therefore, the ideal nondestructive evaluation technique would permit very early detection of fatigue damage so that proper assessment of the severity and rate of severity increase of the structural damage leading to failure can be made. Thus the most sensitive NDE techniques would be capable of detecting motion and pile-up of dislocations; the next most sensitive techniques would be capable of detecting microcracks; the least sensitive systems would be only capable of detecting macrocracks. It is practically expedient to have NDE techniques which can successfully detect fatigue damage in each of these regimes since some components can tolerate larger regions of fatigue damage or larger crack sizes than others without serious concern for the structural integrity of the component.

2.3.2 Fatigue Crack Detection Survey

Historically, nondestructive testing techniques were primarily used to detect the existence of macrocracks in structural materials. Of prime concern in this regard is the size of the smallest flaw which can be detected by each of the nondestructive testing methods. In 1974 W.D. Rummel et al. conducted a comprehensive statistical analysis of the detectability of artificially induced fatigue cracks in aluminum alloy test specimens. They evaluated 118 test specimens containing a total of 328 fatigue cracks. The cracks ranged in length from 0.018 to 1.27 cm and in depth from 0.003 to 0.451 cm. The test specimens were evaluated in the "as-milled" surface condition, in the "etched" surface condition, and after proof testing, in a randomized inspection sequence. The nondestructive test methods used were x-radiography, dye penetrant, eddy current, and ultrasonics. The 984 nondestructive observations taken using each method served as a sample base for establishment of high confidence levels. Based on the results of their measurements, it was concluded that x-radiography is the least reliable of the four test methods for detection of tight cracks and should not be considered as a sensitive, reliable method for detection of tight cracks. On the other hand, the ultrasonic method was

shown to be the most reliable for crack detection as well as to be the most accurate in measuring crack dimensions.

However, the conventional contact ultrasonic techniques can only detect macrocracks and are not able to detect material changes prior to macrocrack formation caused by either fatigue or corrosion damage. The purpose of the present research effort is to develop several non-contact ultrasonic attenuation systems for detection of both fatigue and corrosion damage in aluminum alloy aircraft structures and to select the optimum one for potential practical field applications.

2.3.3 Acoustical Detection of Fatigue Damage

Basically, there are three different acoustical techniques which lend themselves to detection of the onset of fatigue damage namely ultrasonic bulk wave reflection, surface wave reflection, and ultrasonic attenuation.

Bulk Wave Reflection: Bulk wave reflection techniques for fatigue damage detection were first reported in 1964 and have continued to the present time. However, bulk wave reflection techniques are not sensitive to material changes which give warning of fatigue damage prior to macrocrack formation. The main reason for this is that in order for an easily detectable fraction of the incident ultrasonic energy to be reflected from a crack back to the transducer, the crack must be relatively large, and often the structure will already be well on the way to fracture.

Surface Wave Reflection:

Although surface wave reflection techniques have been used since 1962 to detect fatigue cracks, they are not sensitive to material changes which give warning of fatigue damage prior to macrocrack formation. The surface condition of the structure and proper transducer attachment are special problems associated with the use of surface waves. Moreover, in many materials internal stress concentrations cause cracks to form in the interior of the structure and not at the surface where they can be detected by surface waves.

Ultrasonic Attenuation:

The first ultrasonic technique used to study the development of fatigue damage during fatigue cycling was the ultrasonic attenuation technique. As early as 1956, R. Truell and A. Hikata observed changes in ultrasonic attenuation in the early stages of fatigue cycling on polycrystalline aluminum specimens. Similar measurements have continued up to the present time. **Figure 2.2** is representative of the results of measurement of ultrasonic attenuation due to fatigue damage in aircraft aluminum. Note that an easily detectable ultrasonic attenuation change occurred much earlier than an additional pulse due to reflection of the ultrasonic pulse from a crack. Although this technique has been proven to be the optimum one to detect early fatigue damage, it has

not proven useful for field use because of the problem of acoustically coupling the transducer to the structure in a reproducible fashion.

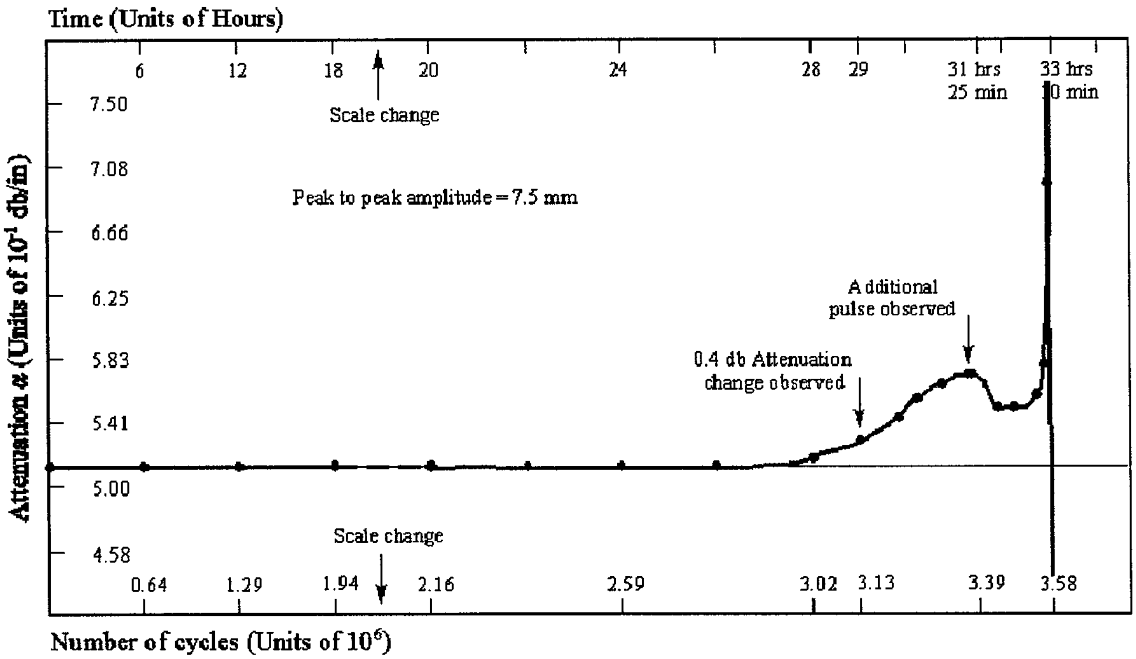


Figure 2.2: Graph of change of ultrasonic attenuation as a function of the number of cycles to failure of an aluminum alloy showing that the ultrasonic attenuation showed a marked increase prior to detection of ultrasound reflected from a crack.

2.4 ULTRASONIC DETECTION OF CORROSION DAMAGE

Although the need to nondestructively detect corrosion damage in military aircraft has been recognized for well over 20 years, the fact that many aircraft currently in service are scheduled to fly well past their original design life up to the year 2040, greatly increases the requirement for a reliable nondestructive method to detect corrosion. Recently a number of efforts have been initiated to nondestructively detect corrosion in aluminum alloy aircraft components. However, to the best of the present investigators' knowledge, none of these techniques involve ultrasonic attenuation measurements. Since any corrosion product on the surface of aluminum alloys will result in an increase in ultrasonic attenuation, this technique also has a very high probability of detecting even small amounts of hidden corrosion.

2.5 AGING AIRCRAFT TESTING

Due to aging, riveted and adhesively bonded aircraft lap joints often develop disbonds, cracks emanating from rivets, and other flaws due to fatigue and corrosion. A reliable nondestructive testing technique for periodic inspections during the service life of

aircraft is essential to detect hidden damage. This is even more critical today, because aircraft are being used many years after their original design life. Because of the structure of aircraft, single sided nondestructive testing techniques are extremely important. Conventional contact ultrasounic NDE techniques have been applied to inspect aircraft lap splice joints. However, for large aircraft area inspection, contact ultrasonic testing has coupling and reproducibility problems. The equipment used for this inspection is very slow because it is complex and must be mechanically assembled, disassembled, and re-assembled in order to inspect the entire structure.

As a result, it is important to develop a rapid and more efficient ultrasonic testing technique. Non-contact air-coupled generation and detection of ultrasound affords the potential for such applications. In fact, because there is no requirement for a coupling medium to transmit the ultrasound, the structure can be inspected remotely and at higher test speed than done with conventional setups. Several non-contact ultrasonic techniques have been investigated using electromagnetic acoustic transducers (EMAT's), lasers, and air-coupled transducers in all possible combinations. EMAT's must be placed very close to the metal surface whereas a laser-based reception system shows low sensitivity, particularly if the surface to be examined is not a good optical reflector. An air-coupled transducer generation/reception system can be used, but due to the large acoustic impedance mismatch between air and solid materials (e.g. aluminum) it is more advantageous to combine laser generation with air-coupled transducer detection. Using laser generation, ultrasound is produced directly on the material surface. By eliminating one of the air/solid interfaces a larger amount of acoustic energy is transmitted into the material, thus improving the detection efficiency of the air-coupled transducer.

Lamb wave modes are very efficient for global inspection of plate like structures or lap joints because they propagate through the whole material or joint area. Since Lamb waves are multimode and dispersive, it is desirable to generate a single Lamb mode so that any change in the received wave signal may be attributed to material integrity or the bond condition. In order to select a single Lamb wave mode we will utilize a spatial modulation technique that employs a periodic transmission mask. Such a mask, illuminated by the expanded laser beam, projects on the sample surface an array of line sources whose spatial frequency represents the wavelength of the generated Lamb mode. By spreading the laser energy over a large area, this technique provides ultrasound generation in the thermoelastic regime that is essential to avoid any damage to the surface of the object under inspection. **Figure 2.3** is an example of Lamb wave ultrasonic response measured over a simplified aircraft lap joint with rivets. Note that the Lamb waves are able to discriminate the disbonds and the rivet regions. The main purpose of this research effort is to develop an efficient non-contact ultrasonic technique suitable for inspection of structure or joints in a reasonable time and with a high degree of accuracy.

This technology has the potential to be extended to aging aircraft systems for detection of corrosion and integrity testing of lap joint rivet or bondline. The system is a novel hybrid ultrasonic configuration consisting of laser generation and air-coupled detection including option for fiber optic light delivery for enhanced system safety,

remoteness and flexibility. This spatial modulation technique generates narrowband ultrasonic surface waves, which permits the following:
* enhanced measurement sensitivity
* control of test depth by adjusting the frequency
* signals detected in single-shot operation
* retention of thermoelastic generation conditions

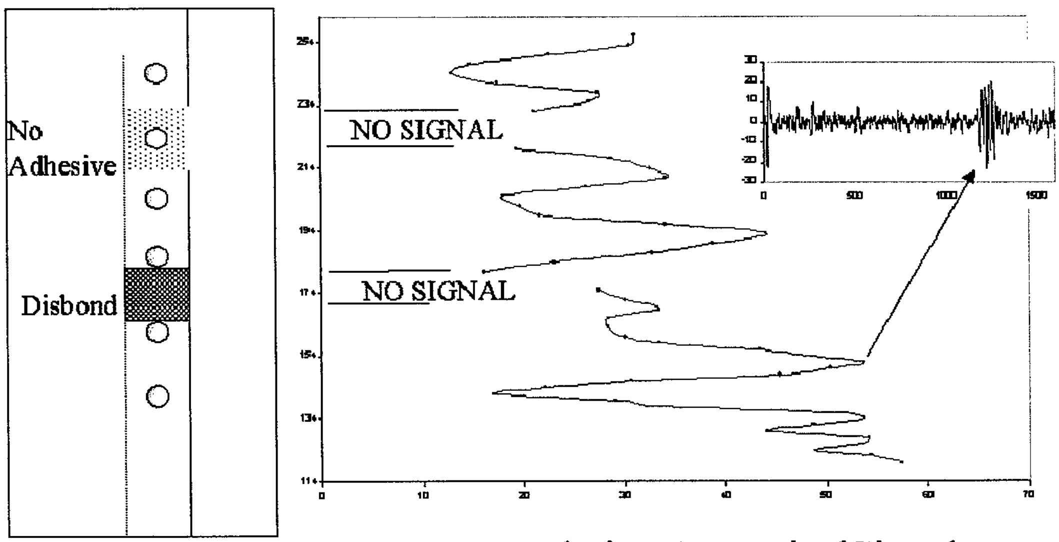


Figure 2.3: Lamb wave ultrasonic response measured over a simplified lap joint with rivets. Lamb waves are able to discriminate the disbonds and the rivet regions of the sample. This data is acquired in a simple one-line scan greatly increasing speed of the tests.

2.6 COMPOSITE PROCESS CONTROL

The process of fiber placement for the manufacture of thermoplastic matrix composite structures requires real time process control and ruggedized nondestructive evaluation (NDE) sensors. Surface acoustical stress wave methods combined with remote laser/air coupled ultrasonic techniques have been applied for on-line process control of fiber placing operations. The Johns Hopkins University CNDE has developed a Hybrid Ultrasonic Remote Inspection System (HURIS™) for non-contact in-process NDE monitoring of fiber placed composite integrity. This system is based on laser ultrasonic and air-coupled ultrasonic transduction methods and the technology has proven feasible for production implementation. Similar laser generation and air-coupled detection systems can be developed and packaged as compact remote sensor test heads for a variety of Naval applications. These systems are usable for both process control and for in-service material structural integrity and damage assessment. A significant advantage

of this method is the ability to examine large areas of material without a need for scanning. Currently, the demonstration HURIS™ is operating at 1.3 MHz to evaluate ultrasonic tests and signals for laser/air coupled transduction methods in a pitch-catch surface wave mode across fibers. A photograph of the test head incorporating laser generation and air-coupled detection is shown in **Figure 2.4** and a schematic drawing of the system is shown in **Figure 2.5**

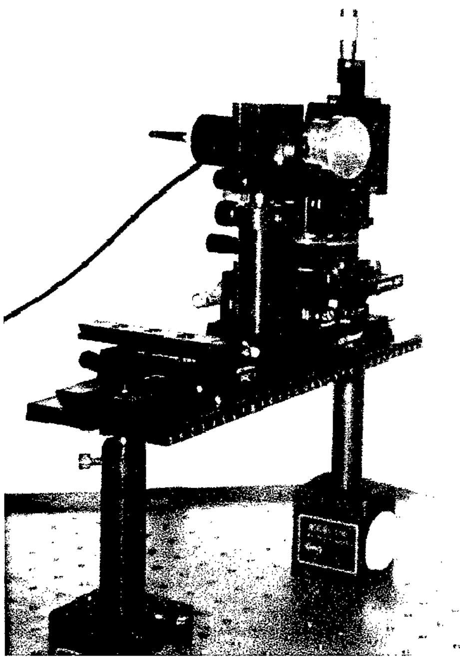


Figure 2.4. Picture of Hybrid Ultrasonic Remote Inspection System (HURIS™) test head incorporating laser generation and air coupled detection of surface acoustic signals for non-contact, in-line inspection of fiber

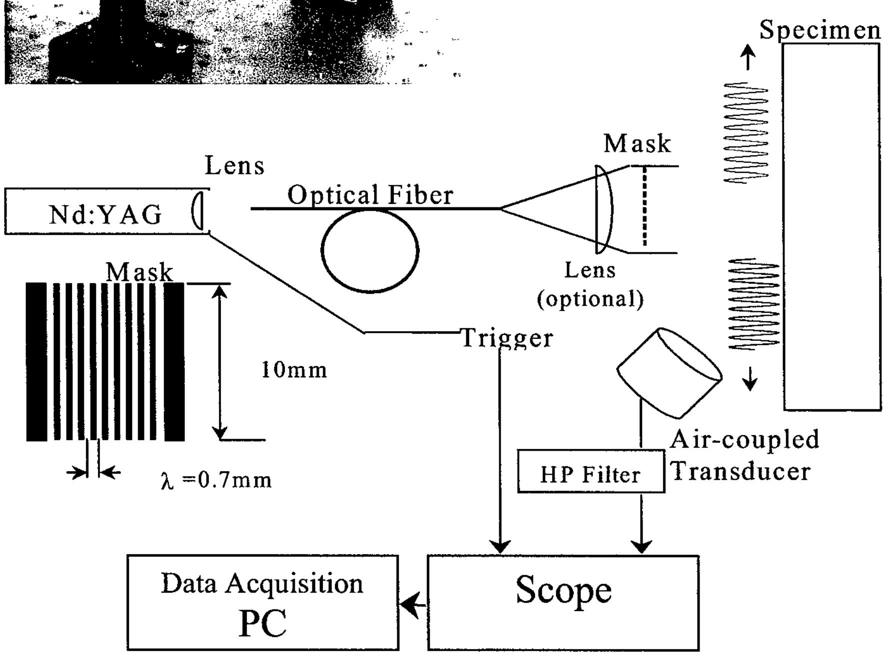


Figure 2.5. Schematic diagram of the elements and functions of the test head components shown in Figure 4 picture.

Using the hybrid ultrasonic system, researchers in the CNDE have achieved remote ultrasonic inspection for process control of both fiber placed composite materials and for composite panel layup. This system meets three key objectives for composite inspection: (1) provides an NDE method for on-line process control of the fiber-tow-placement process for thermoplactic composites, (2) provides truly non-contact remote inspection, (3) provides detection of sub-surface defects in composite panels and their classification.

3.0 TECHNICAL PROGRESS

3.1 RESEARCH EFFORT

The focus of this effort was to develop, optimize and apply remote non-contacting laser and air-coupled technology to enhance means for ultrasonic detection of structural damage due to fatigue or corrosion in bout metal and composite Naval structures. The methods investigated include:

1. laser generation/laser detection ultrasonic systems

2. air-coupled ultrasonic systems

3. hybrid laser generation/air-coupled detection ultrasonic systems

The Johns Hopkins University CNDE has pioneered the development of these techniques from first principles, has carried some of them to the prototype stage, and has demonstrated methodology of non-contact ultrasonic for materials characterization and for the detection of defects such as cracks or disbonds. The instruments developed in the Center for Nondestructive Evaluation at Johns Hopkins University for non-contact ultrasound generation and detection already have a number of distinct advantages when compared to any of the instruments previously reported in the literature or available from instrument vendors. During the course of this project we have developed a new generation of these devices, continued state-of-the-art improvements on them, and have applied these types of non-contact ultrasonic systems to demonstrate, on test samples, nondestructive inspection potentials of this technology for Naval structures.

3.2 RESEARCH RESULTS

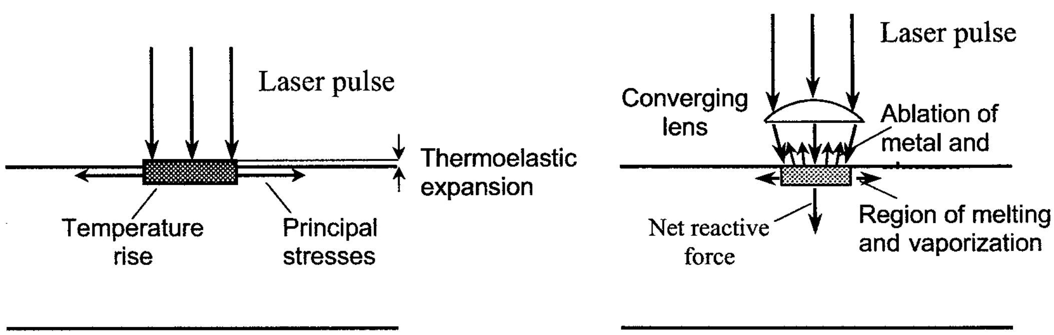
3.2.1 General Transduction and Guided Wave Ultrasonic

The emerging technology of non-contact ultrasonics, enables rapid testing of these structures using ultrasonic tests that are not possible via conventional contact transducers. Laser ultrasonic and air/gas coupled ultrasonic measurements are performed remotely, do not require direct access to test area, do not need traditional ultrasonic coupling and do not have traditional C-scan fixture requirements [1-4]. This hybrid non-contact ultrasonic transduction system extends ultrasonic measurements to test configurations and ultrasonic wave-modes that are difficult to perform using

conventional technology. A Lamb wave or surface acoustical wave can be directed to reach regions of structure not accessible using conventional ultrasonic transducers. Analysis of recorded signals from a single test allows assessments of the defects or material condition. The experimental results demonstrate that such testing techniques can perform the inspection from only one side of the structure. Because there is no requirement for a coupling medium to transmit the ultrasound, and traveling Lamb/surface stress waves cover larger areas, the material or structure can be inspected remotely and at higher test speed than by conventional contact ultrasonic methods. These new, non-contact ultrasonic testing methods, have potential for in-situ evaluation of structural components for the presence of corrosion, cracks and fatigue damage. Experimental tests reported below show feasibility of the technology to support periodic inspections during the service life of a military platform.

3.2.2 Non-contact Ultrasonic Configuration

Figure 3.1 and 3.2 illustrate ultrasonic wave generation via laser light. High-energy, nanosecond pulsed laser illumination of the material surface generates ultrasonic stress



(a) Thermoelastic source (b) Ablative source

Figure 3.1. Ultrasonic wave generation in (a) thermoelastic regime and (b) ablative regime.

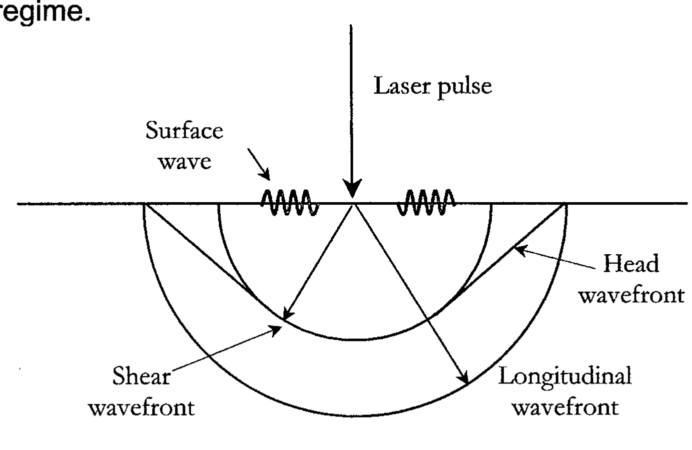


Figure 3.2. Waves generated by a laser pulse incident on an infinite half-space of

waves. The shape, frequency and propagation direction of laser generated ultrasonic waves is controlled by illumination pattern of the laser light. Such acoustical sources are very flexible and enable generation of plate waves (Lamb waves) or surface acoustical waves (Rayleigh waves). Stress waves propagation is effected by material properties, presence of defects or corrosion. In the hybrid ultrasonic test configuration the stress waves are detected by an air-coupled capacitance transducer [5-6].

Signal recorded from a single test as shown in Figure 3.3 allows assessments of the structural and material integrity between the test points. Test configuration can be in bi-static (separate transmitter and receiver points) or mono-static (pulse echo with transmitter and receiver collocated). Presence of cracks, cross-section change, presence of corrosion, delaminations and other defects modulate propagating stress waves and are detected without the need to point-wise scan the complete surface of the part. Analysis of ultrasonic signals enables definition of the material condition between test points. The experimental results demonstrate that such testing techniques can perform the inspection from only one side of the structure. Because there is no requirement for a coupling medium to transmit the ultrasound, the structure can be inspected remotely and at higher test speeds than by conventional contact ultrasonic methods or scanning imaging methods such as ultrasonic C-scan. More technology development is required to fully develop and implement this approach in support of inspections during the service life of a naval structure such as an aircraft.

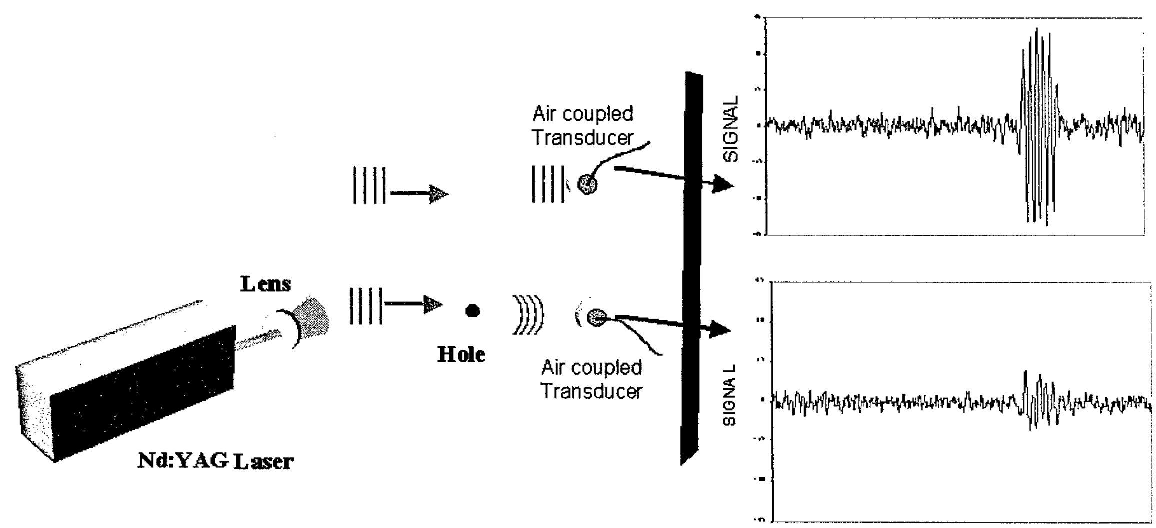


Figure 3.3. Diagram of the hybrid ultrasonic test configuration using laser generation and air coupled detection. This configuration allows large separation between laser generation and air coupled detection points and uses Lamb wave or surface acoustic signals for non-contact inspection. The set-up is adaptable for pulse echo or pitch-catch test configurations. Ultrasonic signals shown in the figure are from an aluminum plate

measured over good area and the area of a plate with a hole. For practical non-contact applications and for lower cost, it is more convenient to combine laser generation and air-coupled transducer detection.[7-8]

For a large aircraft area, contact ultrasonic testing is time consuming. To develop a rapid and more efficient testing technique it is advantageous to perform non-contact ultrasonic measurements that do not require ultrasonic coupling or sophisticated scanning. The plate geometry of many structures including aircraft surfaces readily supports Lamb waves that are hard to induce using conventional transducers and are not commonly used for NDE. Structural and materials testing is possible using Lamb waves (Fig.3.4).

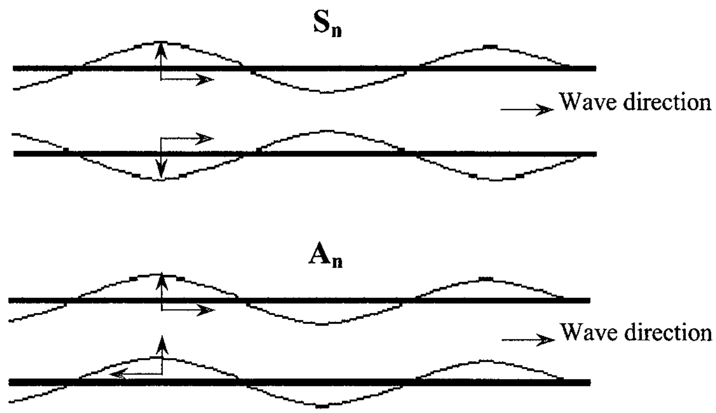


Figure 3.4. Displacement characteristics of symmetric (S_n) and antisymmetric (A_n) Lamb modes. These modes readily propagate over a long distance in the plate like structures. Propagating wave types are better suited for larger area inspection requirements but are less developed than conventional C-scan approach. Both, surface and plate stress wave modes are very sensitive to material integrity, presence of discontinuities (cracks, fatigue induced flaws, and corrosion) or plate thickness changes [9-10].

3.3 TECHNICAL APPROACH

Non-contact ultrasonic tests are performed using laser generation and air-coupled transducer detection. A Q-switched Nd:YAG laser forms a light pattern via lens or transmission mask to generate a selected wave mode. These signals propagate along the plate (skin), interact with defects and are detected by an air-coupled capacitance transducer [11-12]. Figure 3.5 illustrates the detail laser illumination for stress wave generation configured for honeycomb panel testing.

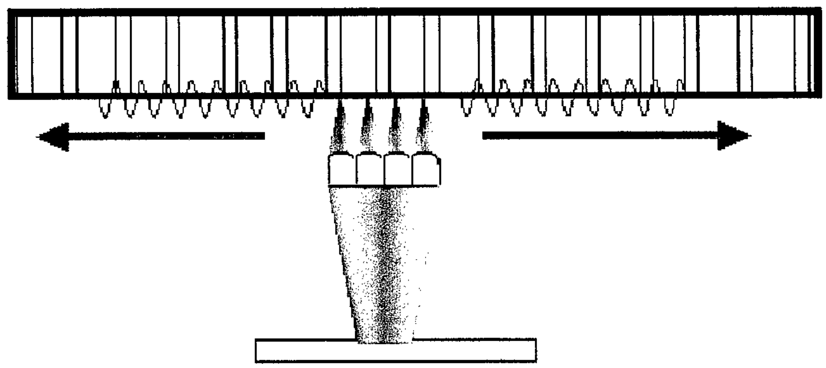


Figure 3.5. Controlled frequency laser ultrasonic set up for testing large area honeycomb panels.

The signal change due to core disbond in honeycomb panel is shown in Fig. 3.6. Amplitude of Lamb wave in panel skin changes over 50% between disbond and good honeycomb bond area.

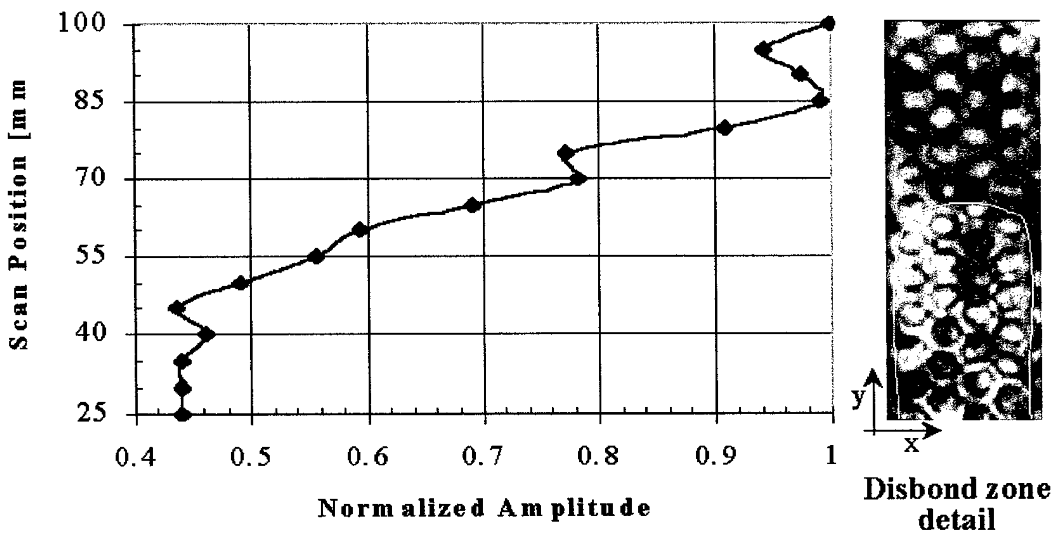


Figure 3.6. Normalized Lamb wave (A_0) signal amplitude as a function of the position along the disbond zone for a honeycomb panel test sample. Disbond detail from Fig. 7.

In contrast, pulse echo ultrasonic C-scan shown in Figure 7 does not significantly change even at acoustical microscope resolutions using 5MHz ultrasonic test signal. The area of disbond cells is outlined on the scan for better location of the defect area.

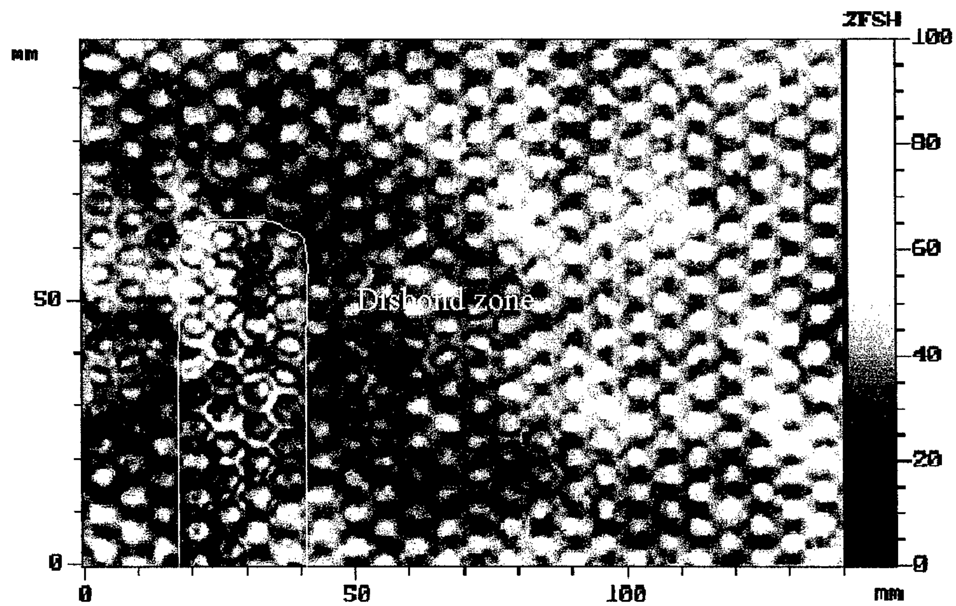


Figure 3.7. Barely detectable honeycomb disbond area detected in pulse echo configuration using 5MHz C-scan with an acoustical microscope.

These non-contact ultrasonic methods are adapted for Lamb and surface wave testing in approximately 100 kHz to 2 MHz frequency range. Lamb wave modes are very efficient for global inspection of plate-like structures or lap joints because they propagate through the whole material or joint area. However, Lamb waves are multimode and dispersive and it is desirable to track the modes or generate a single Lamb mode so that changes in the received wave signals may be attributed to the material condition [13-14]. Figure 3.8 is a diagram of lamb wave modes that were modeled for 1.6 mm aluminum panel. Complex stress wave signals, such as shown in Figure 3.9, can be analyzed using wavelet transforms that give better signal analysis results than traditional frequency spectrum processing. Wavelet analysis enables signal energy allocation to modes that are defined in time-frequency plots. Thus, it is relatively easy to observe mode changes due to the presence of defects and plate geometrical changes that affect plate stress wave propagation. To select a single Lamb wave mode, we utilize a spatial modulation technique illustrated in Figure 3.3 and 3.5. Non-contact ultrasonic configuration enables non-interfering defect detection and materials characterization. Wavelet analysis of signals enables detection and evaluation of the thickness reduction due to corrosion, or defect detection over full sound path, minimizing scanning requirements. This ultrasonic inspection approach overcomes the drawbacks of conventional C-scan imaging and/or contact methods that require point-wise access to all test areas.

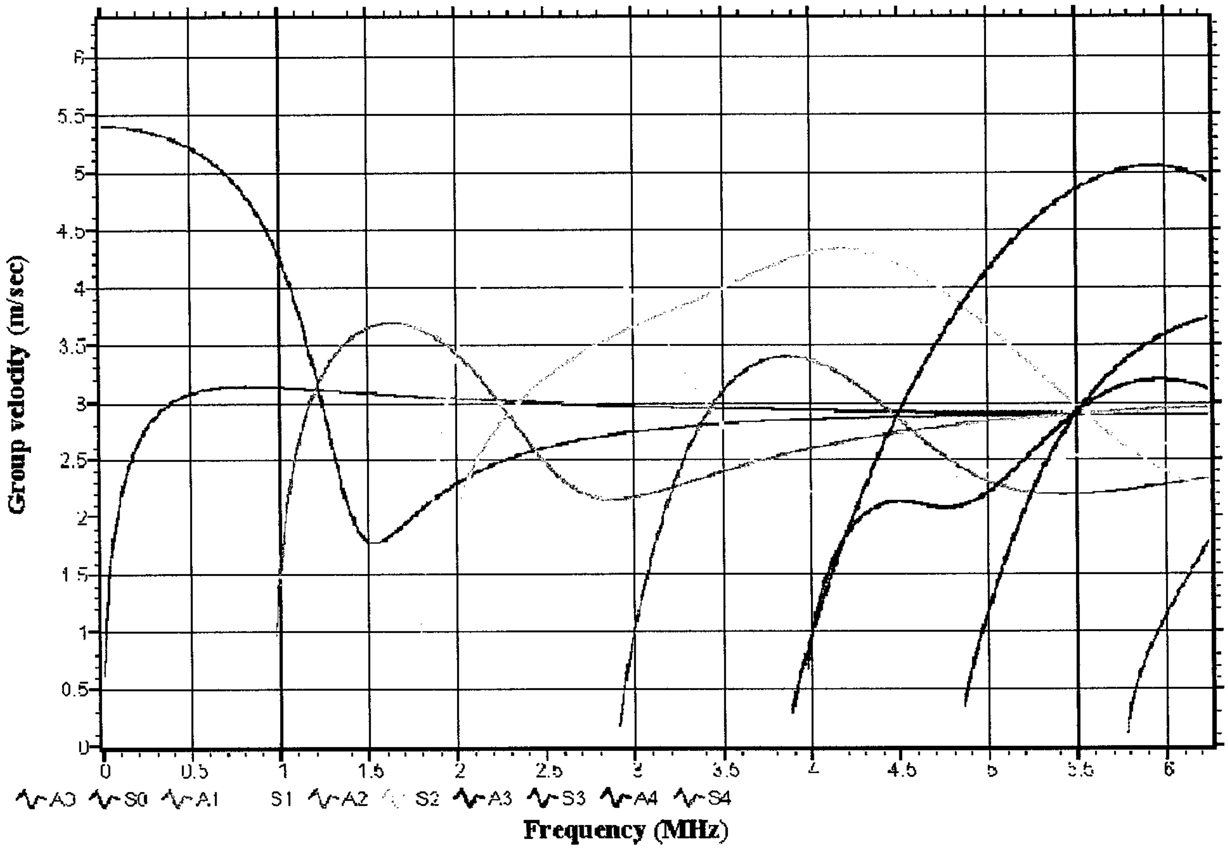


Figure 3.8. Lamb wave modes for 1.6 mm thick aluminum plate typical of aircraft skins.

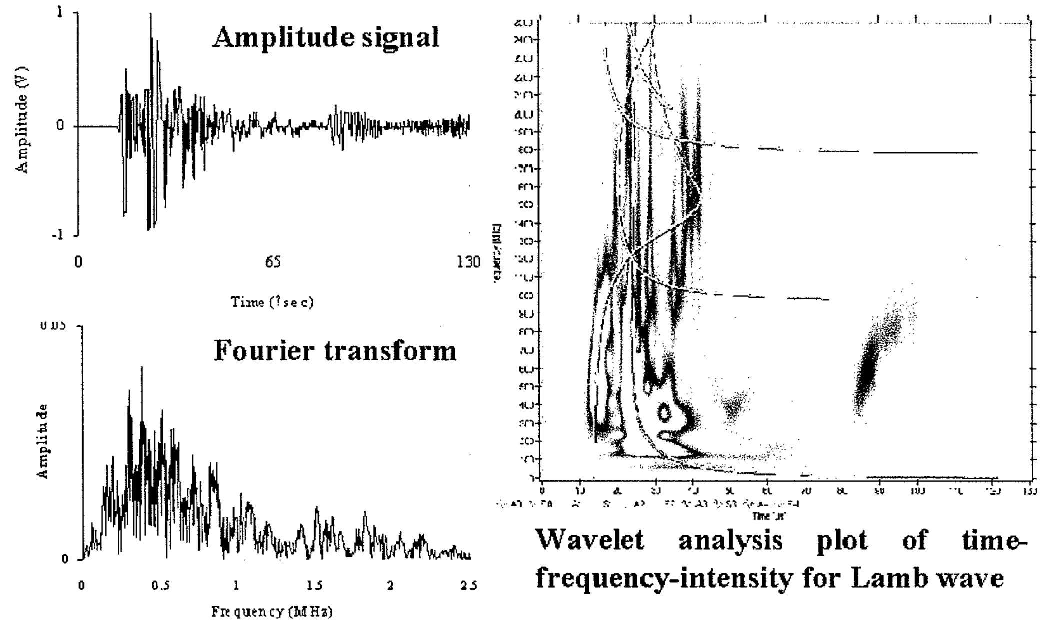


Figure 3.9. Complex plate wave signals analyzed via conventional frequency algorithm and wavelet analysis presentation that distinguishes different modes and signal energy allocation.

Lamb wave ultrasonic tests are performed on a selection of samples and configurations that demonstrate the signal changes due to different sample configurations or reference defects. Figures 3.10 and 3.11 illustrate crack defect effect on propagating multimode Lamb wave. The crack modifies Lamb wave by converting energy of lower frequency modes into higher order lamb modes.

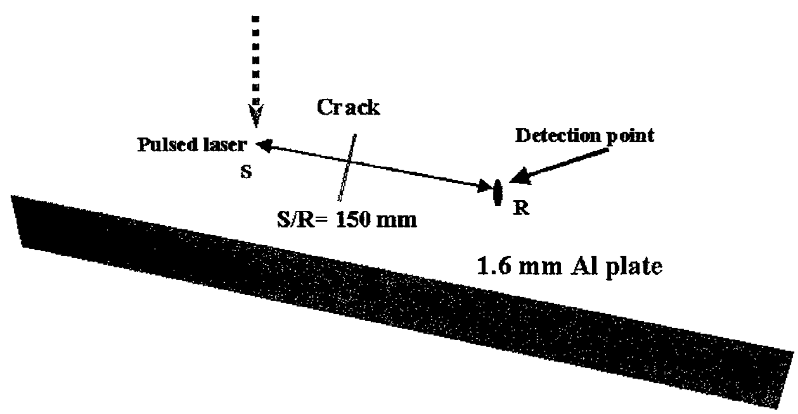


Figure 3.10. Schematic of the experimental test setup.

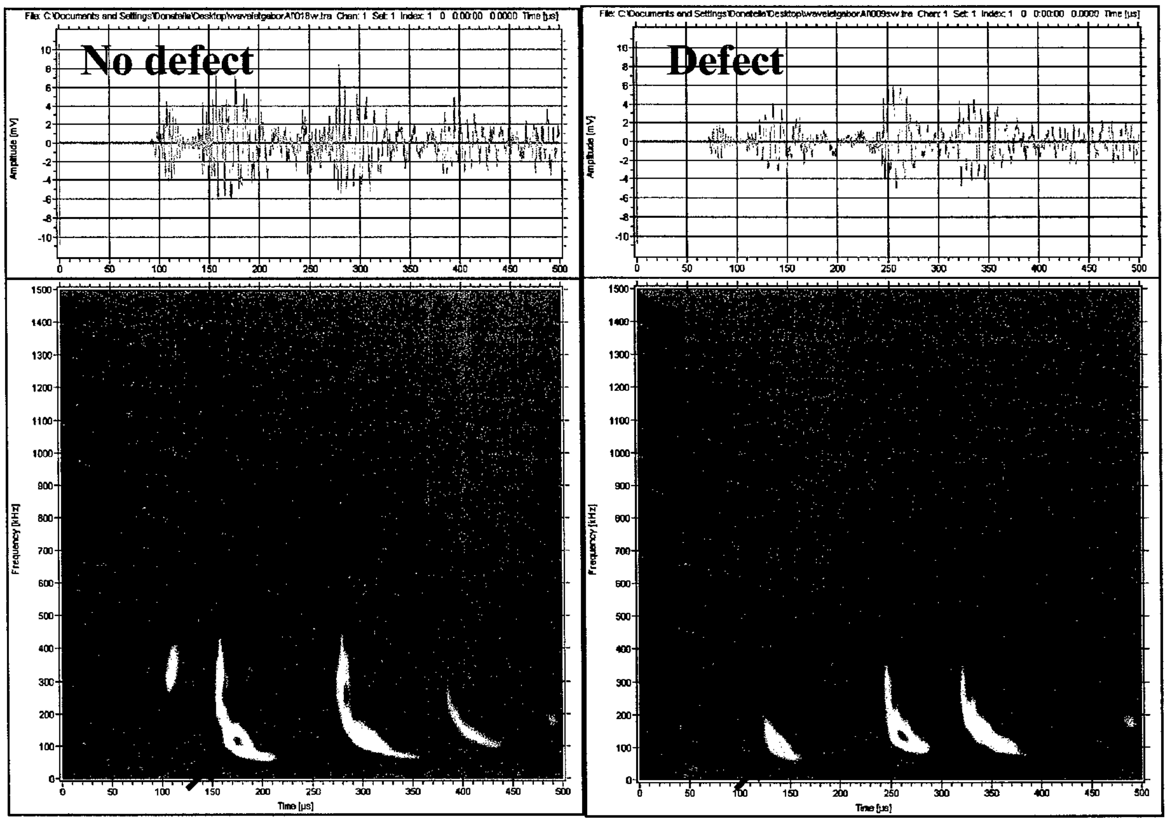


Figure 3.11. Lamb wave signal changes due to presence of skin crack. The wavelet modal analysis diagrams show a loss of energy in lower frequency mode and corresponding ultrasonic energy shift to higher modes when crack discontinuity is present in the sample. The lower mode in the diagrams is highlighted by an arrow.

Lamb wave signal changes for a composite (Gr/Epoxy) step plate is shown in Figure 3.12 recording. Plate thickness changes Lamb waveform signals. The change in modes is readily visible in wavelet analysis diagram that shows shifts in frequency and energy of the wave modes.

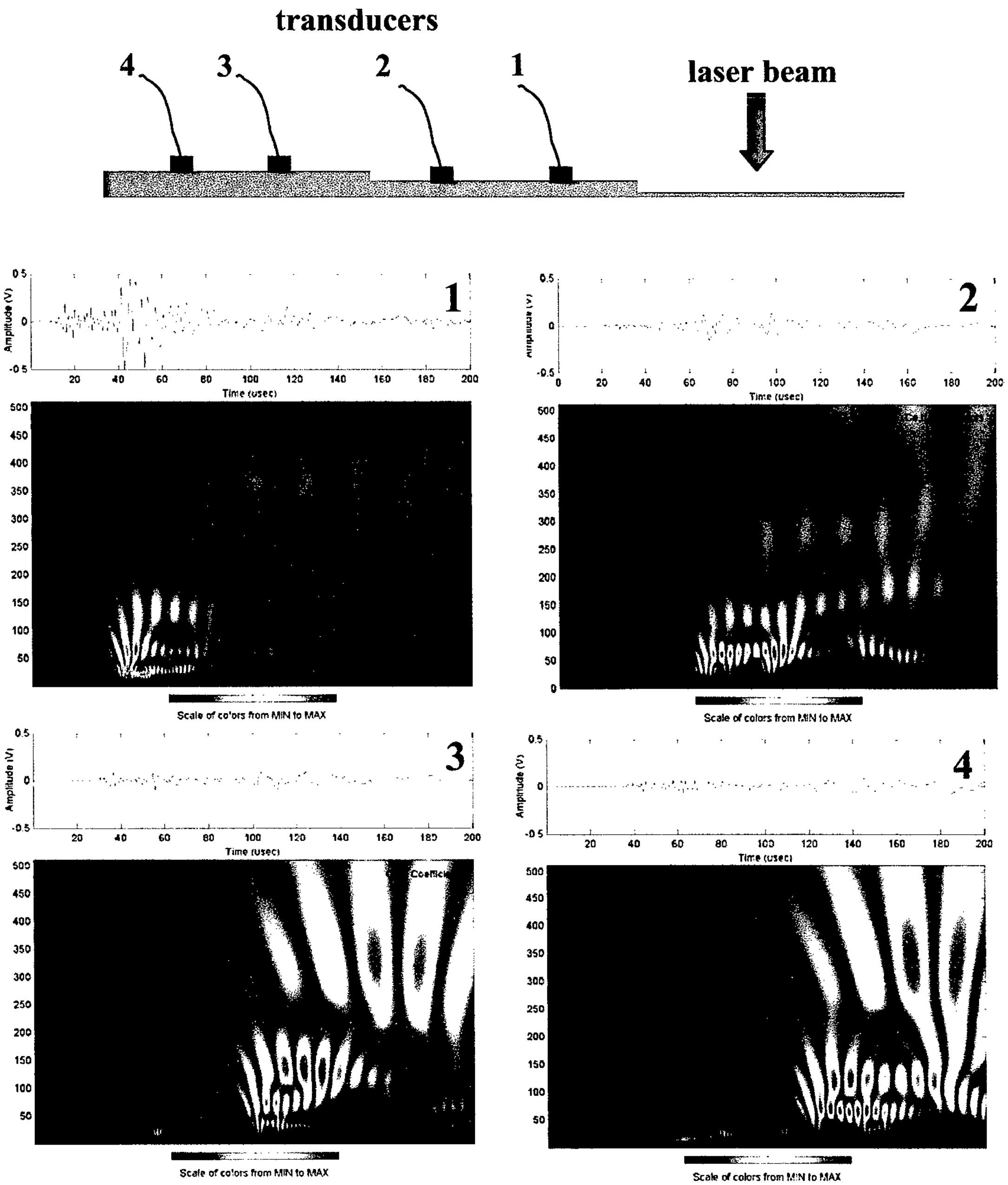


Figure 3.12. Lamb waves in composite step plate change modes and energy distribution as a function of plate thickness and transducer location. Ultrasonic signal generated in thin section readily propagates into the thicker section of the sample.

Figure 3.13 is an example of Lamb wave changes due to presence of crack in the plate. Any cross-section reduction in the plate like structure changes the mechanical boundary and geometry of the plate. This geometry change mandates the interaction with the ultrasonic plate stress waves. Thus, Lamb ultrasonic signal waveforms are modified due to different wave modes in a damaged region of the sample. This response is difficult to discern by examination of direct ultrasonic waveform signal. However, using advanced signal analysis such as wavelet analysis, the changes in modes are readily observed.

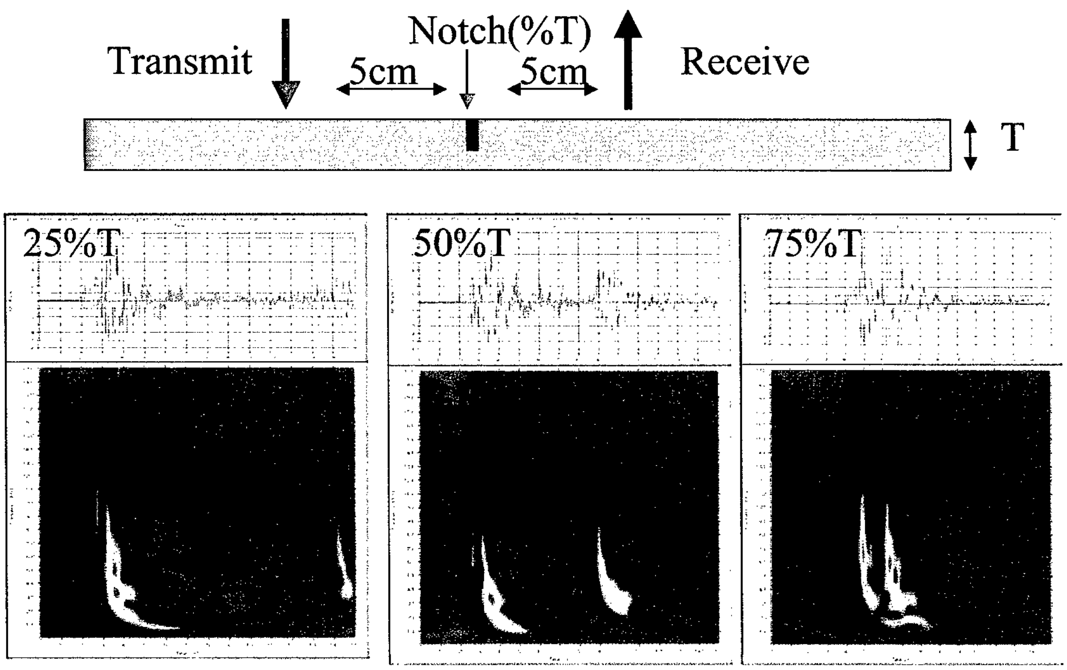


Figure 3.13. Ultrasonic signal amplitude transmission level for different depth of the notch (crack) in plate with thickness T. The wavelet diagrams show significant shifts in modes and mode energy that are influenced by presence of crack like discontinuity. The results indicate the ability to analytically estimate crack depth using the wavelet signal analysis information.

The experimental results on the above panels demonstrate potential to employ this approach for inspection of different aircraft panels. We have performed tests on samples from aged aircraft frames that contained corrosion, disbonds and lap splice with three rows of rivets. The received signal amplitude patterns are more complex, but reflect the

mechanical integrity of the structures. A better data base and more advanced analysis of the signals is required for reliable classification of the measurements. At this point, it is impossible to predict ultimate test sensitivity of this methodology to disbonds or crack size. However, this approach offers very rapid screening for overall structural conditions and the test appears to be very sensitive to any mechanical irregularity.

4.0 CONCLUSIONS

Using hybrid ultrasonic configuration, we have demonstrated a remote ultrasonic inspection methodology to investigate integrity of Naval structures including composites, metal skins and adhesively bonded components. This enabling technology is based on laser ultrasonic and air-coupled ultrasonic transduction methods and the approach is feasible for field implementation. Laser generation and air-coupled reception can be packaged as a compact remote sensor test head for the development of non-contact ultrasonic testing. A significant advantage of the approach is the ability to examine large areas of material without a need for extensive scanning. Laser ultrasonic trunsduction extends ultrasonic measurements to test configurations and wave-modes that are difficult to perform using conventional technology. The hybrid test configuration allows for truly non-contact and remote inspections and incorporates laser light modulation technique for controlled generation of acoustic waves. Experimental results from the samples show that Lamb waves are sensitive to the presence of defects and changes in plate thickness. The tests can be performed with a single line scan, covering large areas by monitoring propagation characteristics of acoustical signals and using wavelet analysis of ultrasonic waveforms.

The experimental results demonstrate that the new, non-contact ultrasonic testing methods have potential for the evaluation of complex components that are not feasible using conventional NDE configurations. Additional work needs to be carried out to establish limits in detection of cracks and corrosion in different type of components and optimization of the test configurations using the hybrid laser/air-transducer ultrasonic system.

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